Search for Exotic Particles at EIC

"Everything is allowed what is not prohibited..."

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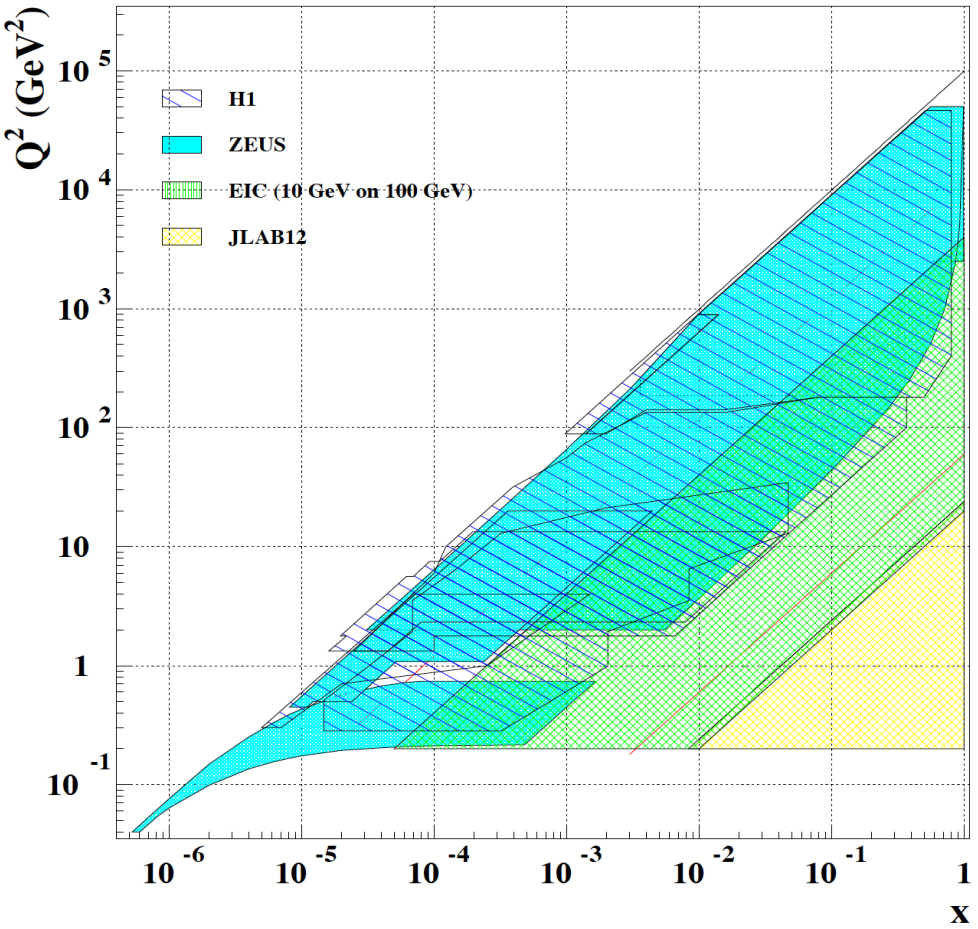
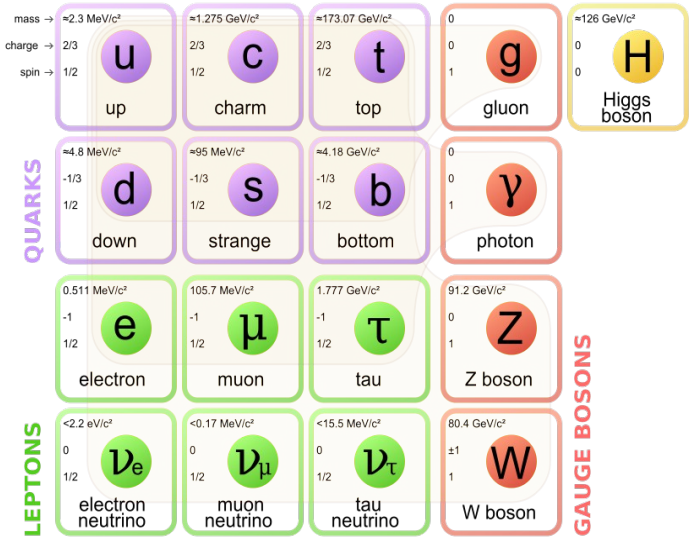
Outline

- Introduction Leptoquarks
- Leptoquarks at EIC
  - Signature
  - Cross section
- Other exotic processes
- Conclusions



Leptoquark (+CLFV)

- SM contains no explanation for the symmetry between quark and lepton sectors. SM does not predict the number of generations.



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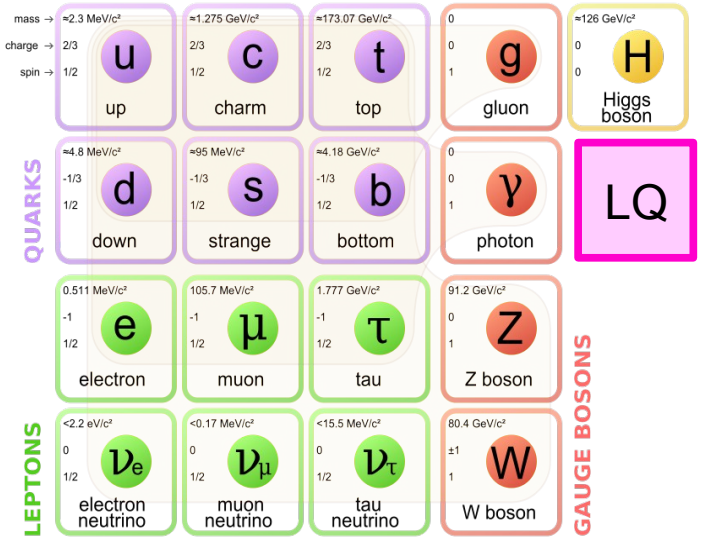
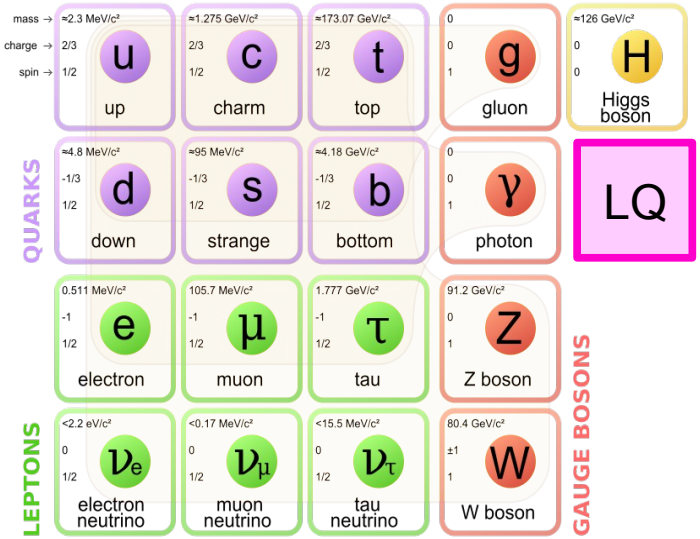
- SM contains no explanation for the symmetry between quark and lepton sectors. SM does not predict the number of generations.
- Leptoquark is a color triplet boson (appear in many SM extensions)



Leptoquark (+CLFV)

- SM contains no explanation for the symmetry between quark and lepton sectors. SM does not predict the number of generations.
- Leptoquark is a color triplet boson (appear in many SM extensions)
- LQs model are explored in Buchmüller-Rückl-Wyler (BRW) framework under SU(3)xSU(2)xU(1) : 14 different LQ types (7 scalars, 7 vectors) .
- Couple to both leptons and quarks and carry SU(3) color, fractional electric charge, baryon (B) and lepton (L) number
- Fermion number F= 3B+L (F= 0, F= 2) is to be conserved



Charged lepton flavor violation (CLFV)

1 generation
$eq \to LQ \to eqX$
$eq \to LQ \to \nu_e qX$
LFC

2 generation
$eq \to LQ \to \mu qX$
$eq \to LQ \to \nu_\mu qX$

3 generation
$eq \to LQ \to \tau qX$
$eq \to LQ \to \nu_\tau qX$

CLFV

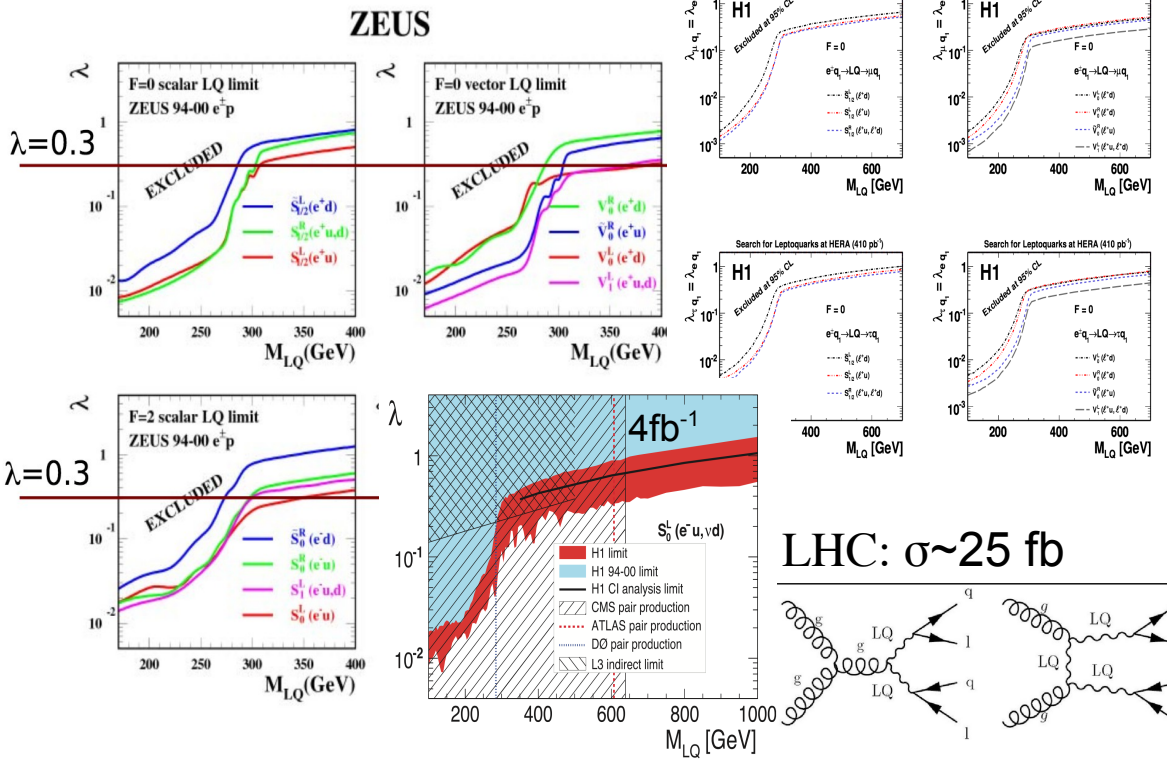
Charged Lepton Flavor Violation (CLFV)

- With discovery of Neutrino oscillations, we know that lepton flavor is not conserved
- Is it also not conserved for charged leptons?
- At EIC CLFV : $eq \rightarrow \mu q$ or $eq \rightarrow \tau q$

- Detector requirements :
  - 4π muon detector
  - 4π hadronic calorimeter (to identify a missing energy from neutrinos)

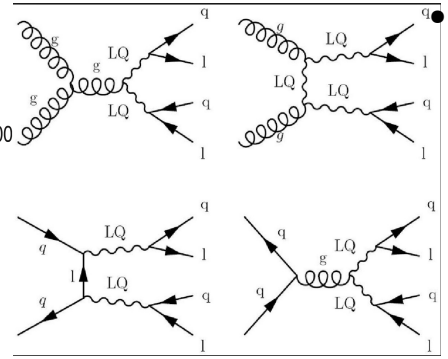
Leptoquark limits

LQ->eq

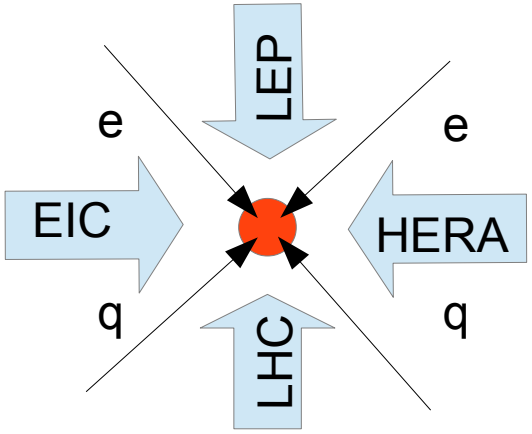


LQ->μq and LQ-> τq

LHC: σ~25 fb



For leptoquark Yukawa coupling λ = 0.1, the ZEUS bounds on the first-generation leptoquarks range from 248 to 290 GeV



- LEP (ee):contact interactions (indirect constrains from e^+e^--> $q\bar{q}$)
- LHC/TEVATRON (pp): pair production (λ independent)
- HERA/EIC (ep): single LQ production M<√s, contact interaction M>√s

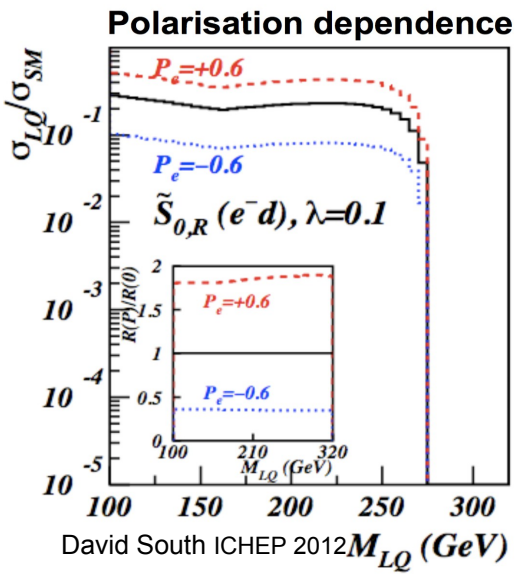
HERA: L~$10^{30\text{-}31}$ $cm^{-2}s^{-1}$ (0.5 fb^{-1})
EIC: L~10^{34} $cm^{-2}s^{-1}$ (>50 fb^{-1})

Leptoquarks at EIC

Type	J	F	Q	ep dominant process	Coupling	Branching ratio β_ℓ
S_0^L	0	2	$-1/3$	$e_L^- u_L \to \ell^- u$	λ_L	1/2
				$\nu_\ell d$	$-\lambda_L$	1/2
S_0^R	0	2	$-1/3$	$e_R^- u_R \to \ell^- u$	λ_R	1
$\tilde{S}_0^R$	0	2	$-4/3$	$e_R^- d_R \to \ell^- d$	λ_R	1
S_1^L	0	2	$-1/3$	$e_L^- u_L \to \ell^- u$	$-\lambda_L$	1/2
				$\nu_\ell d$	$-\lambda_L$	1/2
			$-4/3$	$e_L^- d_L \to \ell^- d$	$-\sqrt{2}\lambda_L$	1
$V_{1/2}^L$	1	2	$-4/3$	$e_L^- d_R \to \ell^- d$	λ_L	1
$V_{1/2}^R$	1	2	$-1/3$	$e_R^- u_L \to \ell^- u$	λ_R	1
			$-4/3$	$e_R^- d_L \to \ell^- d$	λ_R	1
$\tilde{V}_{1/2}^L$	1	2	$-1/3$	$e_L^- u_R \to \ell^- u$	λ_L	1

Type	J	F	Q	ep dominant process	Coupling	Branching ratio β_ℓ
V_0^L	1	0	$+2/3$	$e_R^+ d_L \to \ell^+ d$	λ_L	1/2
				$\bar{\nu}_\ell u$	λ_L	1/2
V_0^R	1	0	$+2/3$	$e_L^+ d_R \to \ell^+ d$	λ_R	1
$\tilde{V}_0^R$	1	0	$+5/3$	$e_L^+ u_R \to \ell^+ u$	λ_R	1
V_1^L	1	0	$+2/3$	$e_R^+ d_L \to \ell^+ d$	$-\lambda_L$	1/2
				$\bar{\nu}_\ell u$	λ_L	1/2
			$+5/3$	$e_R^+ u_L \to \ell^+ u$	$\sqrt{2}\lambda_L$	1
$S_{1/2}^L$	0	0	$+5/3$	$e_R^+ u_R \to \ell^+ u$	λ_L	1
$S_{1/2}^R$	0	0	$+2/3$	$e_L^+ d_L \to \ell^+ d$	$-\lambda_R$	1
			$+5/3$	$e_L^+ u_L \to \ell^+ u$	λ_R	1
$\tilde{S}_{1/2}^L$	0	0	$+2/3$	$e_R^+ d_R \to \ell^+ d$	λ_L	1

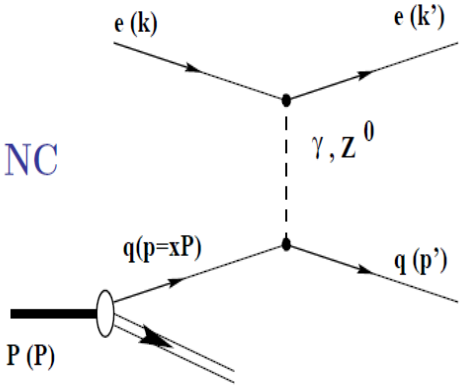
- High luminosity (~100-1000 higher then HERA)
  - HERA: $L \sim 10^{30\text{-}31} cm^{-2} s^{-1}$ (0.5 fb^{-1})
  - EIC: $L \sim 10^{34} cm^{-2} s^{-1}$ (>50 fb^{-1})
- Electron and positron beam will probe different types of Leptoquarks
  - -electron-proton collisions, mainly F=2 LQs produsedd
  - -positron-proton collisions, mainly F=0 LQs produsedd
- eD (deuterium) vs ep collisions
- LQs are chiral particles, gain in sensitivity due to polarised beams

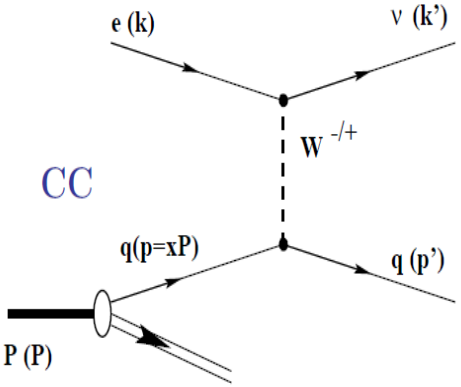


David South ICHEP 2012

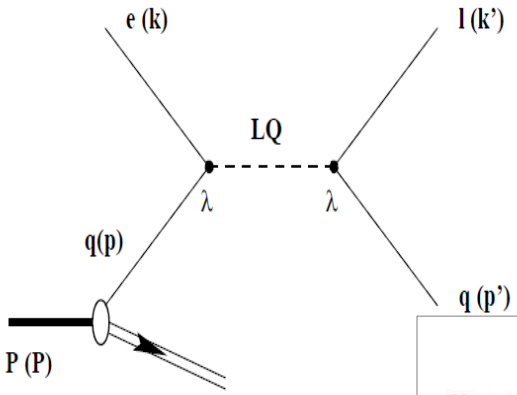
Leptoquarks production

DIS at EIC



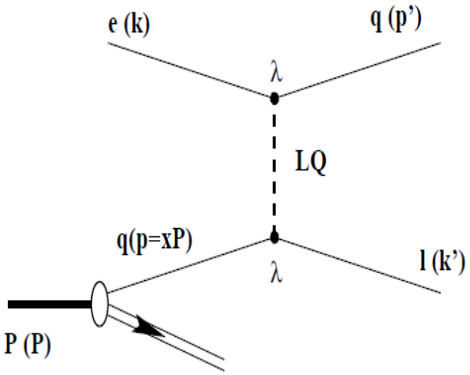


LEPTOQUARKS at EIC



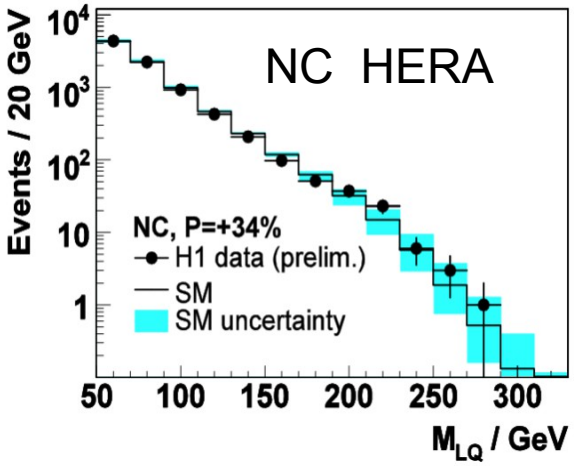
$$x = \frac{M_{LQ}^2}{s}$$

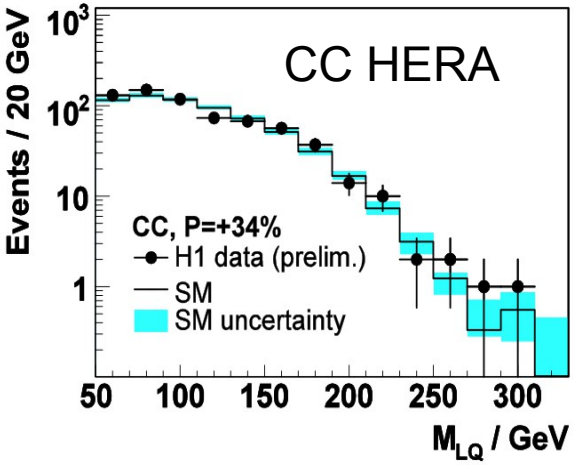
s-channel
(resonant production)
$M_{LQ} < \sqrt{s}$



u-channel
(LQ exchange)
$M_{LQ} > \sqrt{s}$

Leptoquark search mass spectra

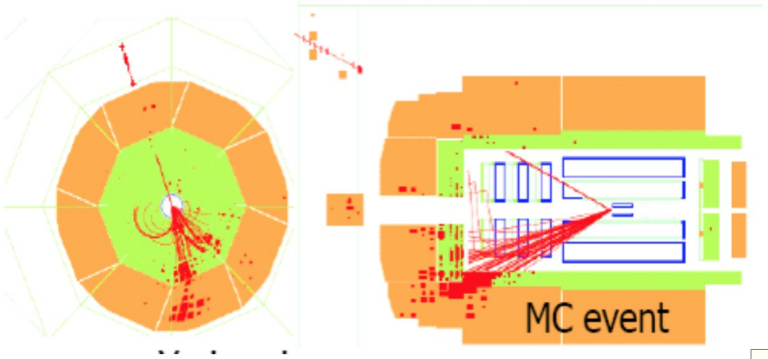




Leptoquark signature

- 14 different LQ types (7 scalars, 7 vectors) . All 14 couple to electron and quark (NC-like), and only 4 couple to both eq (NC-like) and νq (CC -like)

Signature ep->μX



LQ signature

CC-DIS like

- Missing P_T + jet (ν+jet)

NC-DIS like

- Back to back topology (l+jet)

High Pt isolated lepton, balanced by a jet in transverse plane

Tau + jet (CLFV)
(ep->τq)

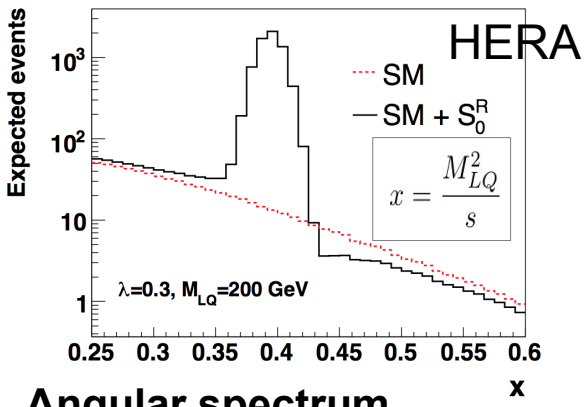
$\tau \rightarrow e \nu_e \nu_\tau$
$\tau \rightarrow \mu \nu_\mu \nu_\tau$
} BR~ 36%

Hadronic decay
Narrow "pencil" like jets
(1-3 pions)

Electron + jet
ep->eq

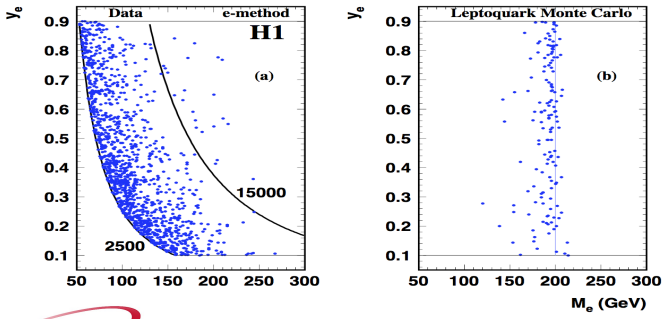
Muon + jet (CLFV)
ep->μ q

Leptoquark

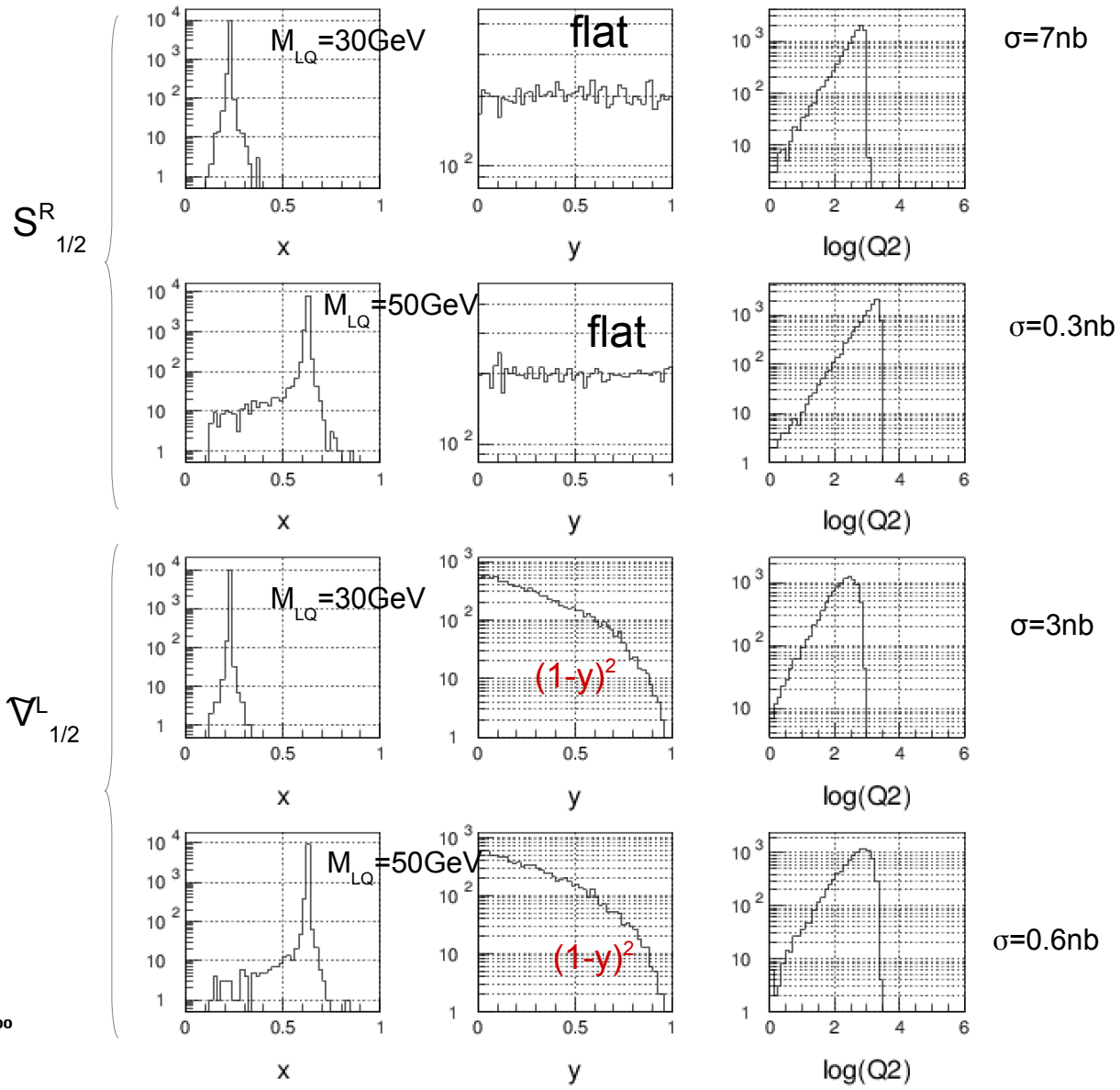


Angular spectrum

- Scalar LQ (s-channel) or Vector (u-channel) – decay isotropically => cosθ* or y dependence is flat
- Vector LQ (s-channel) or Scalar LQ (u-channel) – $(1-y)^2$ dependence.
- DIS background: $1/y^2$
- Artificial Neural Network



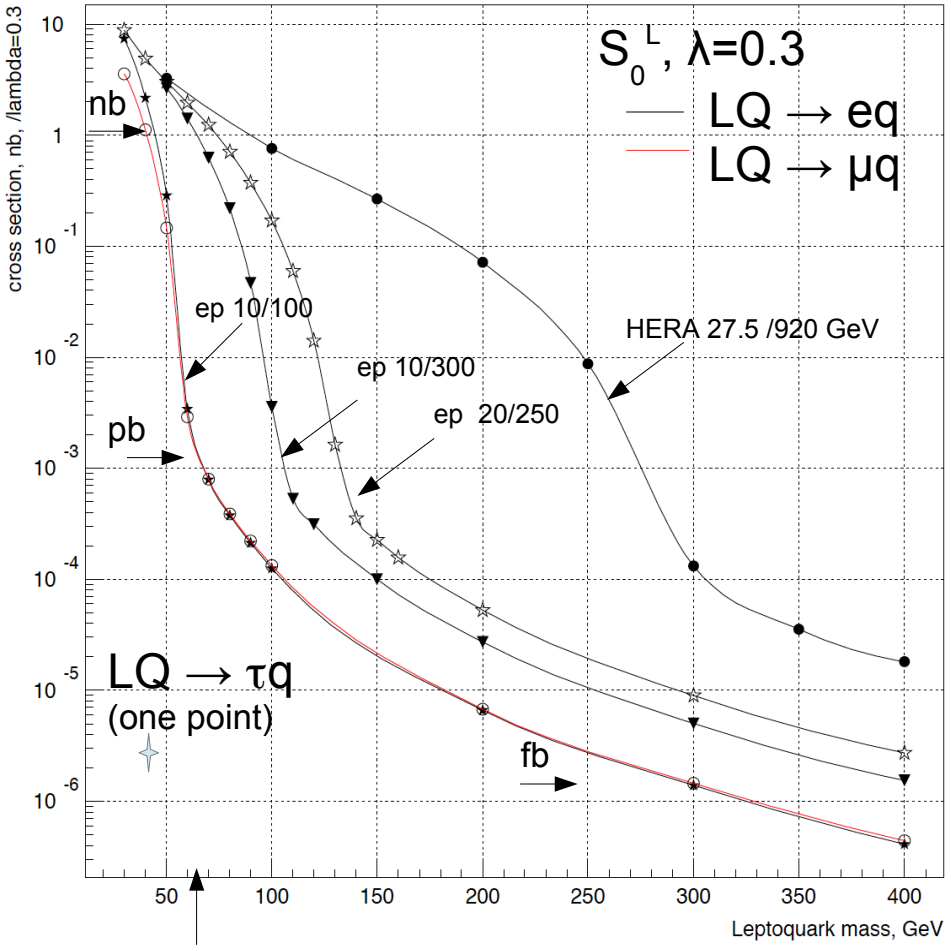
EIC: e- 10 GeV, p 100GeV, λ=0.3



LQ cross section at EIC

LQgenEP Monte Carlo
λ=0.3 ep=10,100 GeV

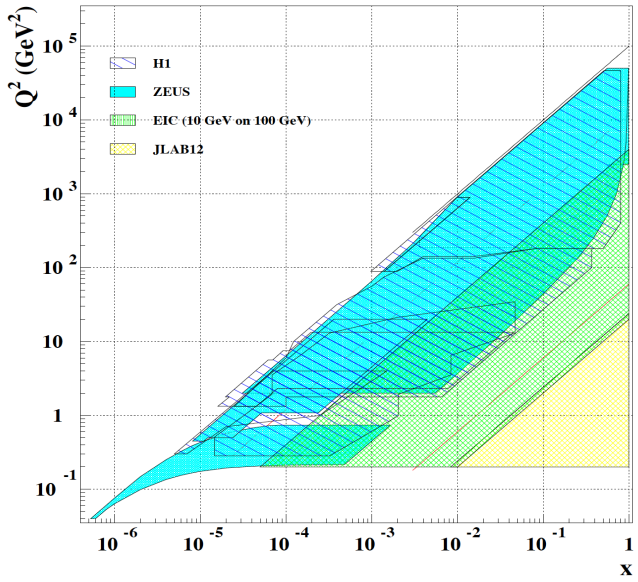
LQ type	Process 1-st gen.	BR	σ(nb) for M_{LQ}=50GeV	σ(fb) for M_{LQ}=150GeV
S^L_0	$e^-u \to e^-u$ $e^-u \to \nu d$	50% 50%	0.29	21.0
S^R_0	$e^-u \to e^-u$	100%	0.56	21.5
$\tilde{S}^R_0$	$e^-d \to e^-d$	100%	0.09	8.0
S^L_1	$e^-d \to e^-d$ $e^-u \to \nu d$ $e^-u \to e^-u$	50% 25% 25%	0.49	54.2
$V^L_{1/2}$	$e^-d \to e^-d$	100%	0.18	15.3
$V^R_{1/2}$	$e^-d \to e^-d$ $e^-u \to e^-u$	13% 87%	1.32	45.8
$\tilde{V}^L_{1/2}$	$e^-u \to e^-u$	100%	1.13	31.1



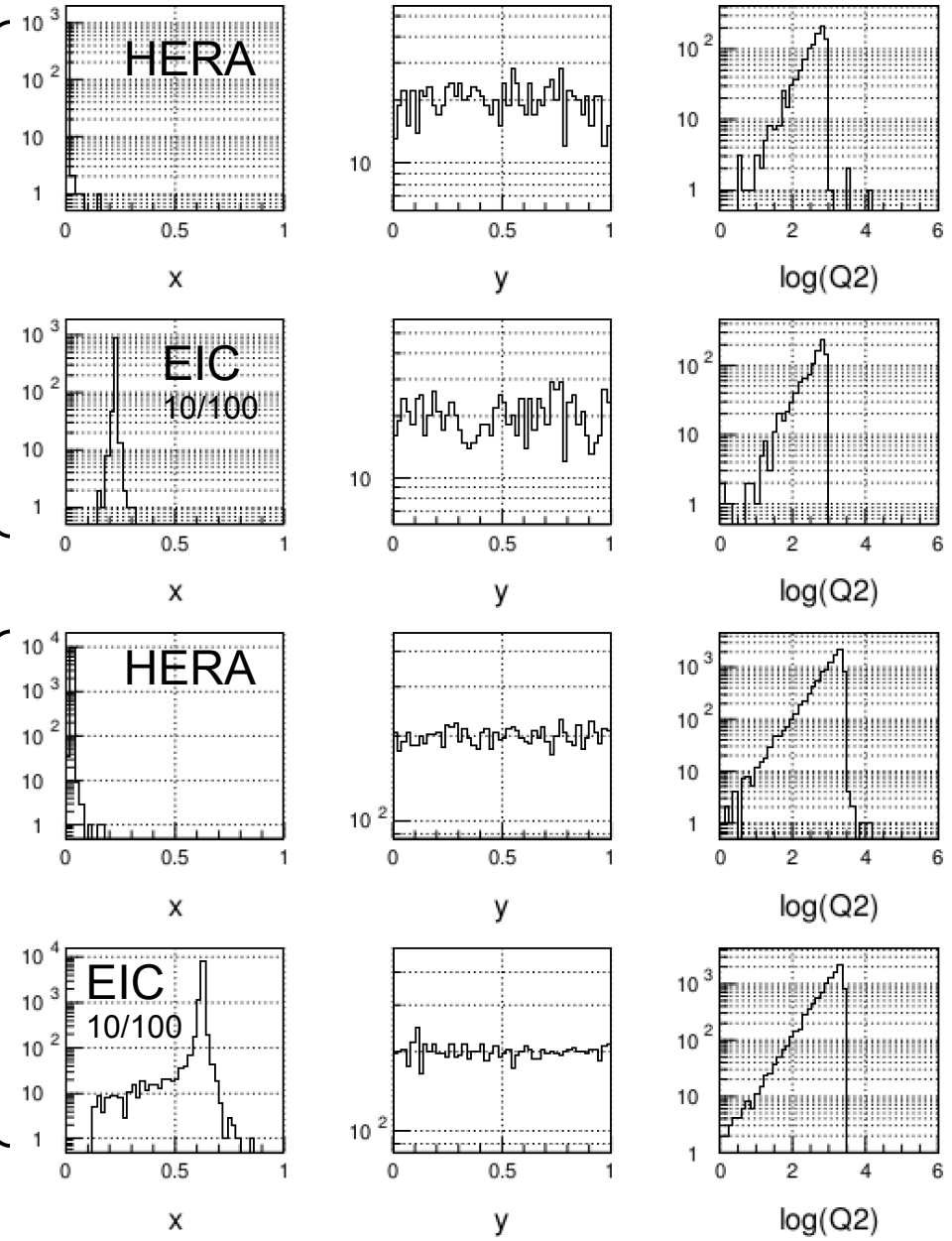
HERA: $L \sim 10^{30\text{-}31} cm^{-2} s^{-1}$ (0.5 fb^{-1})
EIC: $L \sim 10^{34} cm^{-2} s^{-1}$ (>50 fb^{-1})

Leptoquark

M_{LQ}=30GeV



M_{LQ}=50GeV



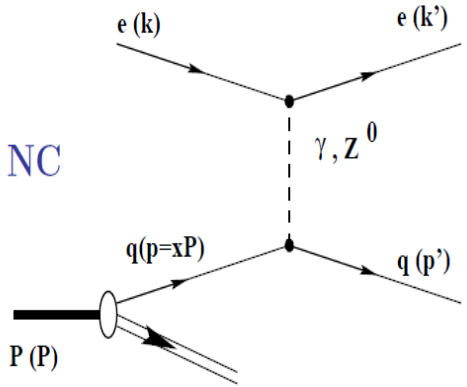
Typical HERA selection cuts:

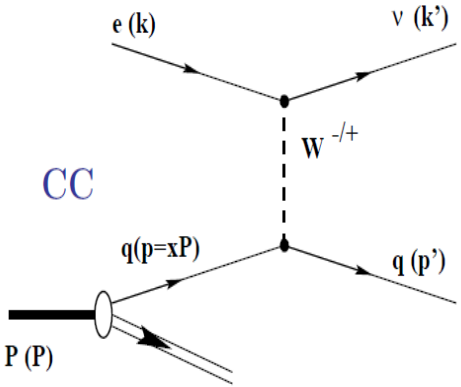
- x>0.1
- Q^2> 2500 GeV^2

Leptoquarks with $M_{LQ} > \sqrt{s}$

$$\frac{d^2\sigma}{dxdQ^2} = \frac{d^2\sigma_{SM}}{dxdQ^2} + \frac{d^2\sigma^{Int}_{s/SM}}{dxdQ^2} + \frac{d^2\sigma^{Int}_{u/SM}}{dxdQ^2} + \frac{d^2\sigma_s}{dxdQ^2} + \frac{d^2\sigma_u}{dxdQ^2}$$

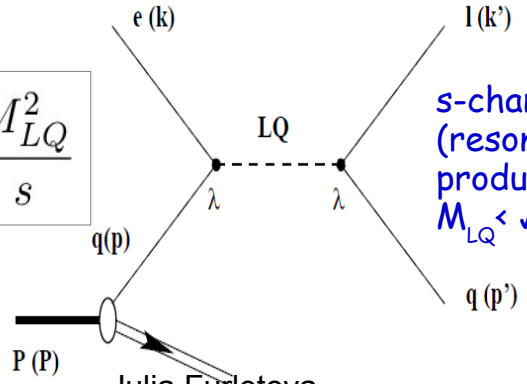
DIS at EIC



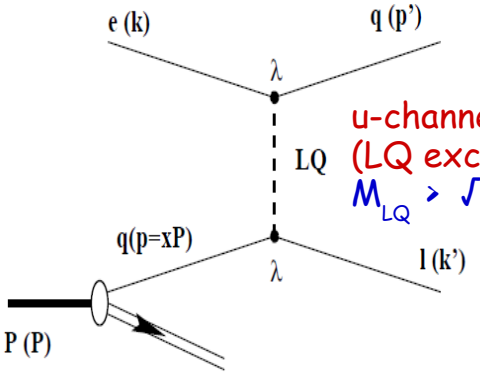


LEPTOQUARKS at EIC

$$x = \frac{M^2_{LQ}}{s}$$



s-channel (resonant production) $M_{LQ} < \sqrt{s}$

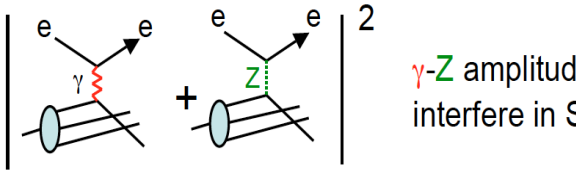


u-channel (LQ exchange) $M_{LQ} > \sqrt{s}$

LQ and DIS Parity

Cross section

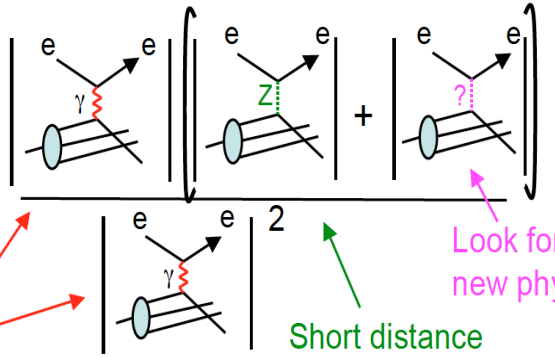
$$\sigma_R + \sigma_L \sim$$



γ-Z amplitud
interfere in S

PV Asymmetry

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim$$

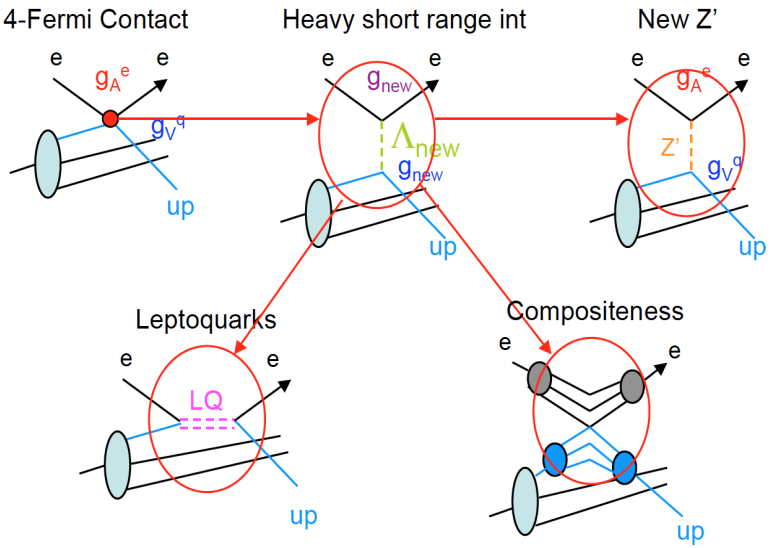


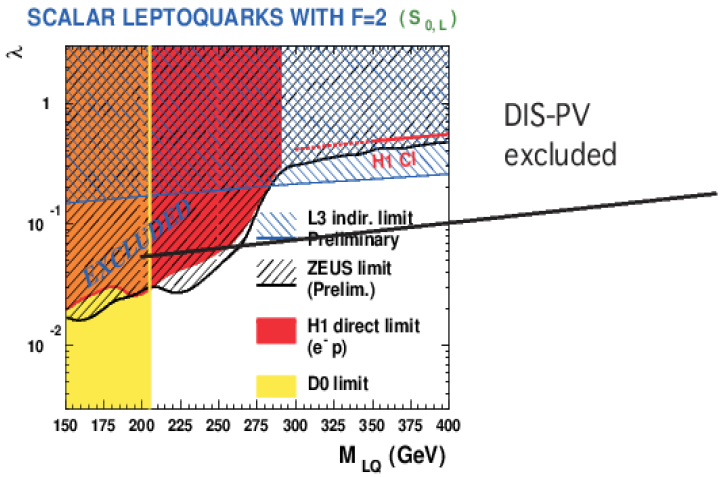
γ–q large and
well understood

Short distance
e-Z-q probe
SM value known

Look for small
new physics

New Physics Can Modify e-q Coupling





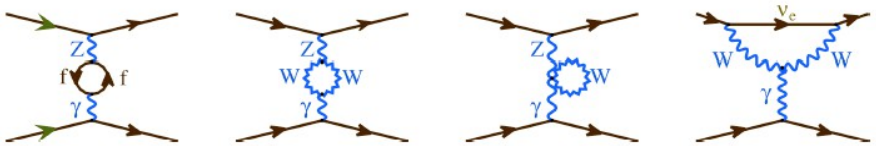
DIS-Parity will provide complementary information to direct search and will significantly extend the limit on the existence of leptoquarks beyond the currently set in direct searches

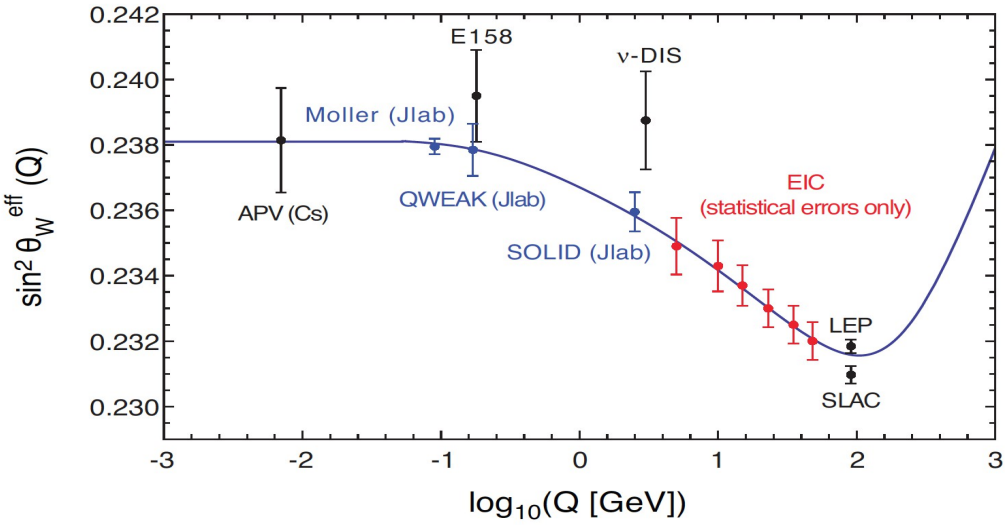
DIS-Parity could put limit M_{LQ}>2.4 TeV

R. Arnold, DIS-Parity SLAC EPAC

Running of $\sin^2(\theta_W)$ with Q^2

- Measurements of a weak mixing angle





- Deviation from the "curve" may be hints of BSM scenarios including: Lepto-Quarks, RPV SUSY extensions, E_6/Z' based extensions of the SM

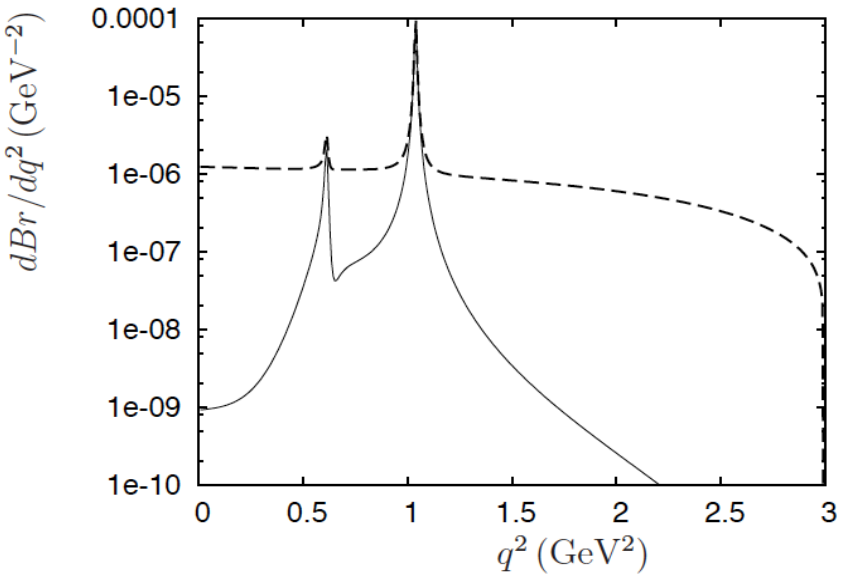
Flavor changing neutral current (FCNC)

- Search for rare or SM- forbidden decays of a charmed mesons

$c \to u\, l^+ l^-$

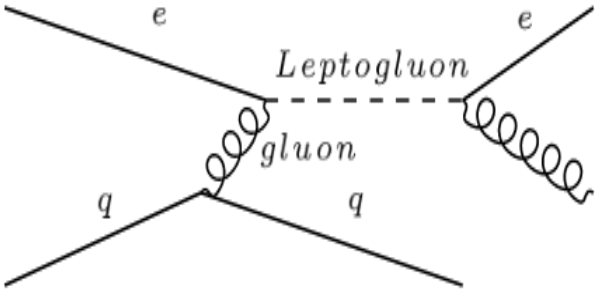
$Br(D^+ \to \pi^+\mu^+\mu^-) < 3.9 \times 10^{-6}$

- Search for a scalar leptoquark coupling in the $D^+ \to \pi^+ l^+ l^-$ decay or $D \to \mu^+\mu^-$



S. Fajfer, arXiv:0810.4858v1

Resonant production of Leptogluons

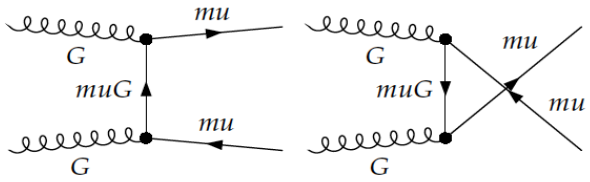


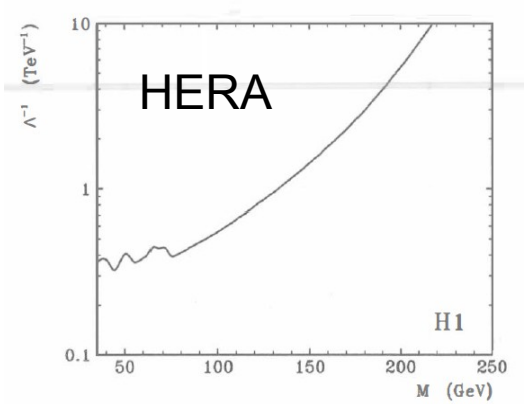
-Leptogluons are color-octet states.
-Carrying lepton number and couple to gluons

Color octet charged leptons e8: m_8>86 GeV[CDF: Abe, PRL 63, 1447]
HERA: excluded scale region Λ<1.8 TeV for m_8~100GeV
New bound on e8 mass: m_8 > 1.2TeV [Goncalves-Netto et al., 2013]

Signature:
Electron and gluon jet
(different jet fragmentation compared to a leptoquark)

LHC: muonic leptogluon μ_8 t-channel exchange
(di-muon channel) σ(pp->μμ) ~ 1fb





LHC: m_8 > 1.5TeV for √s=8TeV and Λ= 3.4TeV

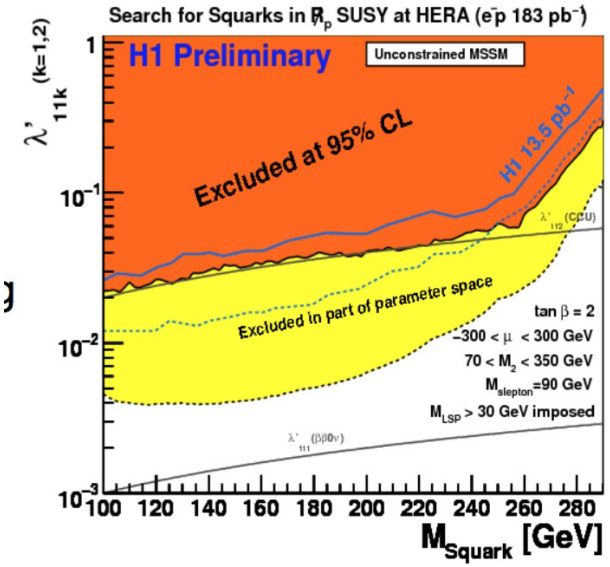
arXiv:1511.05814 Y. C. Acar
"Leptogluons for FCC"

"Collider Searches for Leptogluons "
-D. Zhuridov.

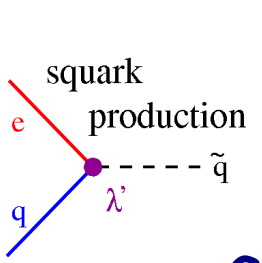
SUSY search

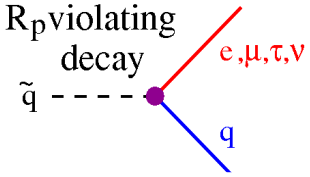
- R-parity: $R_p = (-1)^{L+3B+2S}$
  (R_p = +1 for SM particles,
  -1 for SUSY particles)

- If RPV: single resonant squark production possible in ep collisions



Squark production





Lepton+jet: Leptoquark searches

Gaugino Search

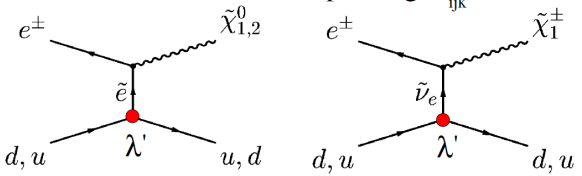
If $M_{squark} \gg M_{slepton}$:

s-channel suppressed $\Rightarrow$ t-channel dominant, probing λ'_{ijk}

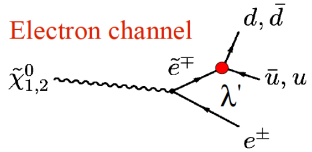
Gaugino production:

$\sigma \sim (\lambda')^2$

Independent of squark masses!

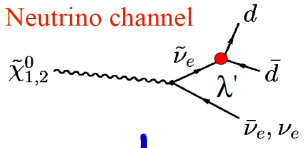


Gaugino Decay:



BRs add up to almost 100%.

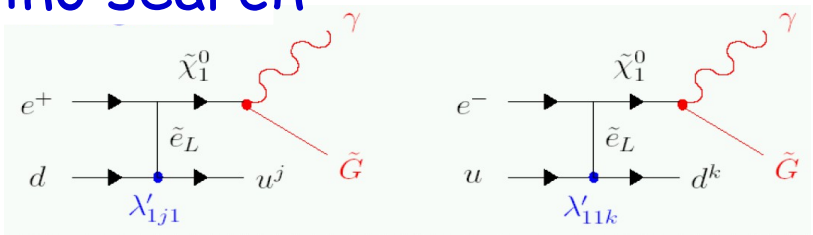
$\tilde{\chi}^{\pm}$ decay to same final states



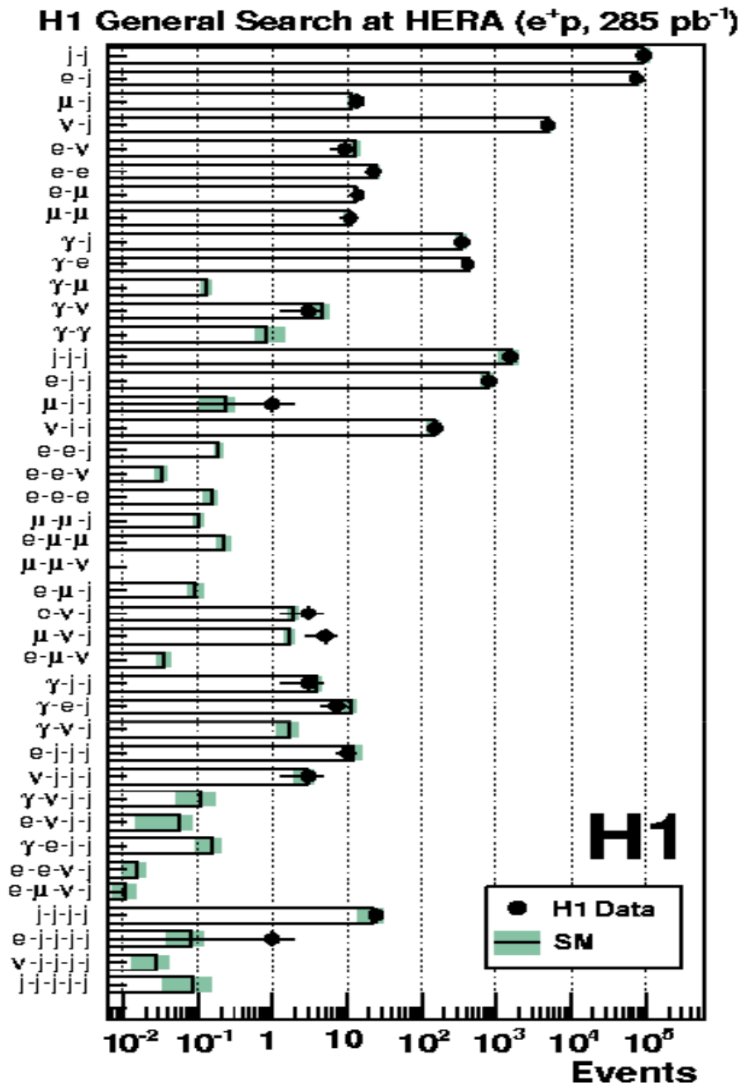
C. Horn SUSY 2006

Gravitino search

Signature:
γ, jet, $P_{T,miss}$



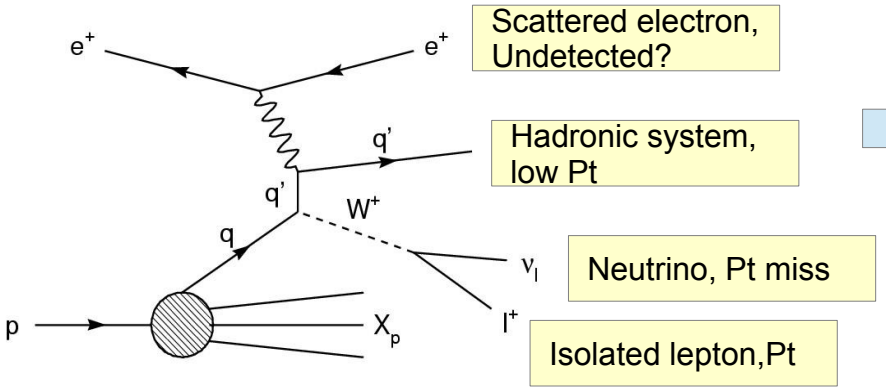
General search for New Phenomena



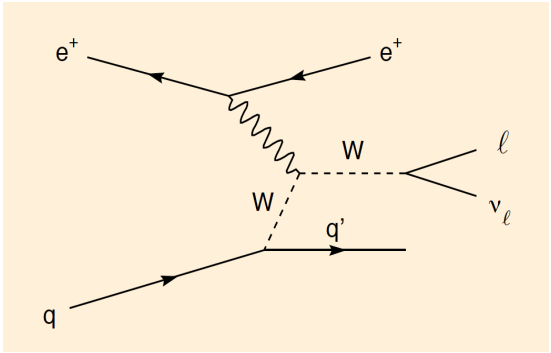
- Model independent generic search for final states with ≥ 2 objects (e, μ, jet, γ, ν)
- Look for possible deviations from SM in total event number and in Σp_T and Mass distributions

Multi leptons and isolated leptons with missing P_T

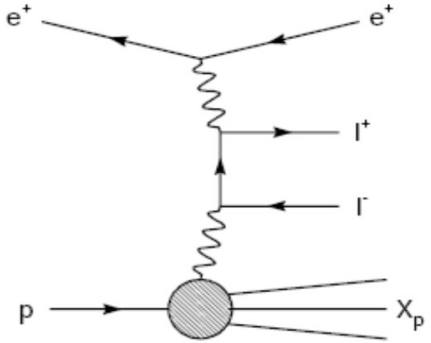
SM process with isolated lepton and P_T^{miss}



Anomalous triple gauge WWγ couplings



Multi-leptons in γγ process: look for deviation from SM - resonances



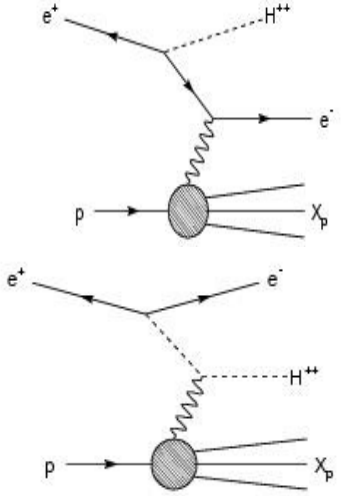
Resonance production,
e.g. Doubly-charged Higgs bosons ($H^{\pm\pm}$)

H±± decays into ee, eμ and eτ pairs

HERA limit:

In ee channel $H^{\pm\pm}$ <138 GeV are excluded for a coupling $h_{ee} = 0.3$.
In the $e\mu$ channel masses below 141 GeV are excluded for a coupling 0.3

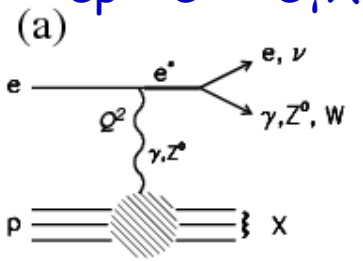
In the $e\tau$ channel masses below 112 GeV are excluded for a coupling 0.3



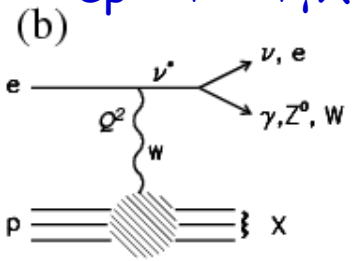
Excited Fermions

- Production via t-channel $\gamma(Z^0)$,W exchange
- Lepton de-excitation by emission of γ
- Observation would be direct evidence for compositeness
- Compositeness could explain the three lepton/quark families and their mass hierarchy

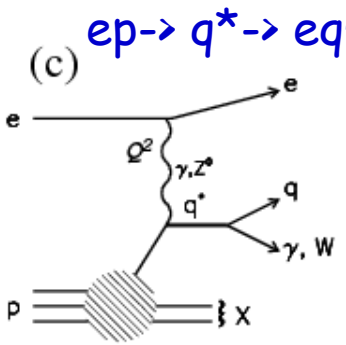
ep-> e*-> eγX

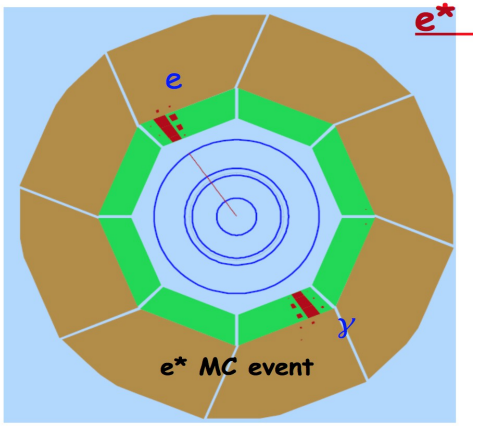


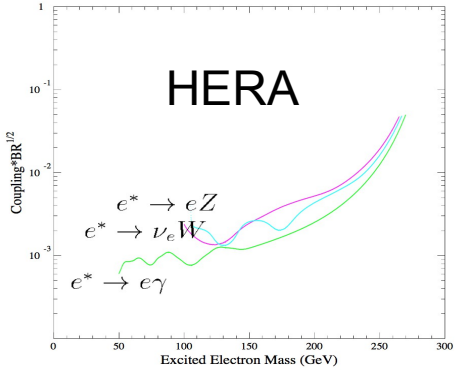
ep-> ν*->$\nu\gamma$X

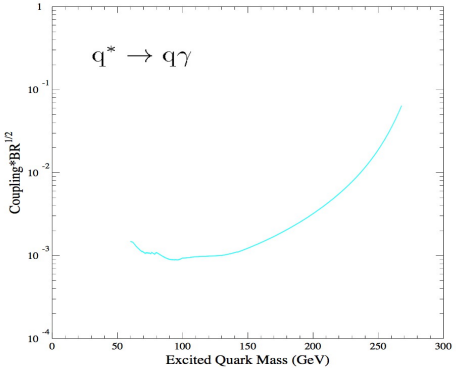


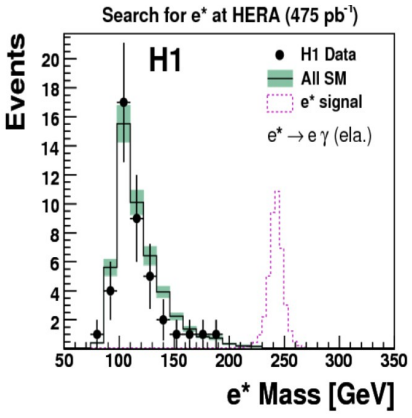
ep-> q*-> eqγX

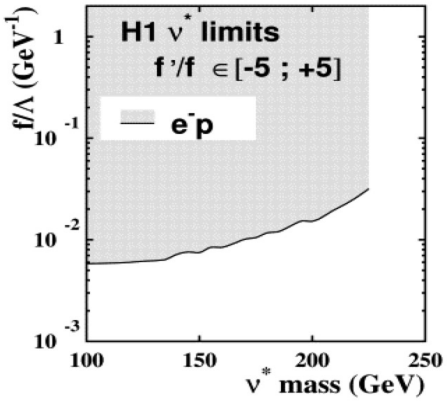








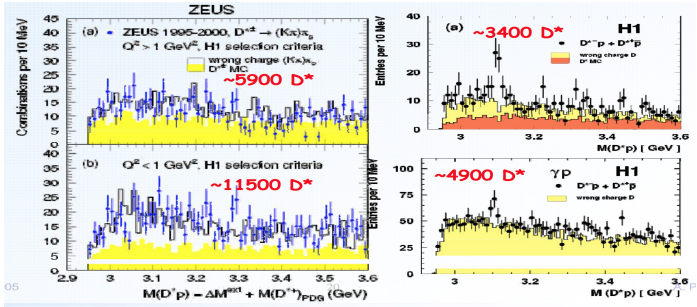




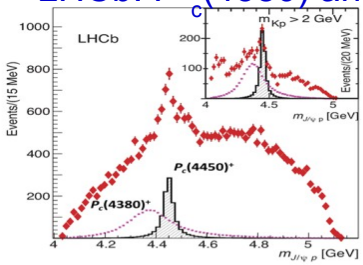
Pentaquarks at EIC

(talk by Justin Stevens)

- QCD: only colorless states can exist as free particles: qq (mesons), qqq (barions)
- Other colorless combinations (QCD) not forbidden:
- $qqqq$ (tetraquarks), $qqqq\bar{q}$ (pentaquarks)
- $\Theta^+[uudd\bar{s}]$ (1.53GeV) -> K^+n (LEPS, CLAS, SAPTHIR).
- Evidence for $\Xi^{--}(ddss\bar{u})$, $\Xi^0(udss\bar{u})$ by NA49 (pp $\sqrt{s}$ =17 GeV)
- Charmed pentaquarks $\Theta^c[uudd\bar{c}/\overline{uuddc}]$ ẁ D*p ZEUS vs H1 comparison



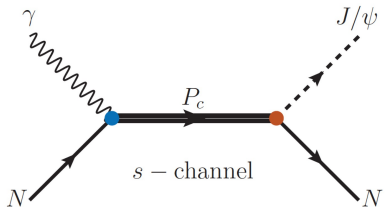
- LHCb: $P^+_c(4380)$ and $P^+_c(4450)$



Possible search for Pentaquarks in photoproduction

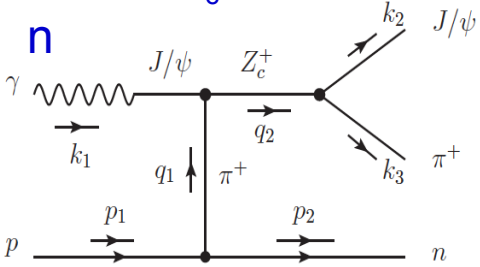
-photoproduction of hidden charm pentaquarks

$P^+_c[uc\bar{c}ud](4380)$ and $P^+_c(4450)$



-Tetraquarks: probe the new XYZ states and heavyquark hybrid mesons

γ p-> $Z^+_c[c\bar{c}u\bar{d}]$ (3900) + n



- Low-Q2 electron and neutron (close to beam pipe) detection
- Excellent e/π separation

-Potential bottomonium production Zb(10610) and Zb(10650) similar to observed at Belle

Conclusions

- High luminosity, polarization, possibility to switch to e+, and comparison of data for ep and ed (eA) are essential for Leptoquark searches.
- 4π detector with perfect calorimetry (EM and HCAL) and with 4π muon detectors are beneficial for physics BSM.

"Everything is possible! The impossible just takes a little longer..."

Backup